

New physics search using **Europium nuclei in a crystal**

Bassam Nima



University of Toronto, Canada

EDMs2026 : WE-Heraeus Workshop

Outline

- Why do we use a crystal platform for new physics probes?
- How do we make our measurements?
- How much can we improve our sensitivity?

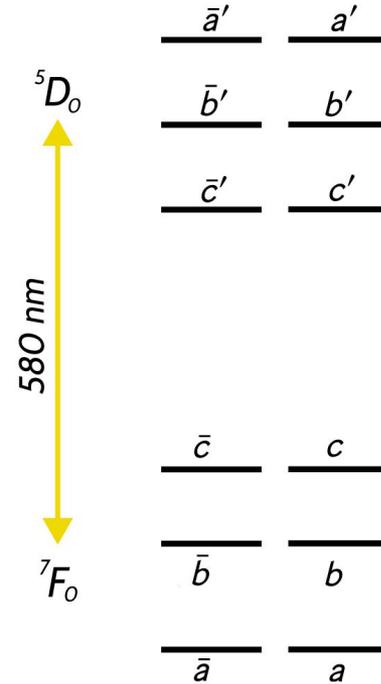
Europium-153

- Stable isotope
- Nuclear spin-5/2
- Nucleus is octupolar: nuclear Schiff moment enhancement

$$\overline{5/2} \quad \overline{3/2} \quad \overline{1/2} \quad \overline{-1/2} \quad \overline{-3/2} \quad \overline{-5/2}$$

Europium ions doped in yttrium orthosilicate (YSO)

- $^{153}\text{Eu}^{3+}$ is doped into non-centrosymmetric Y sites, where ions are polarized by the large crystal field
- 0.01% doping gives 10^{14} ions to probe in a $\sim\text{cm}^3$ crystal
- At 4 K, ions are in the quantum ground state
- No need for optical trapping or laser cooling



Hamiltonian

$$H = \sum_{i,j} Q_{ij} I_i I_j - \mu_x \mathcal{B}_x + \mu_y \mathcal{B}_y - \mu_z \mathcal{B}_z - D \hat{n} \cdot \vec{\mathcal{E}} + \Omega \vec{I} \cdot \hat{n}$$

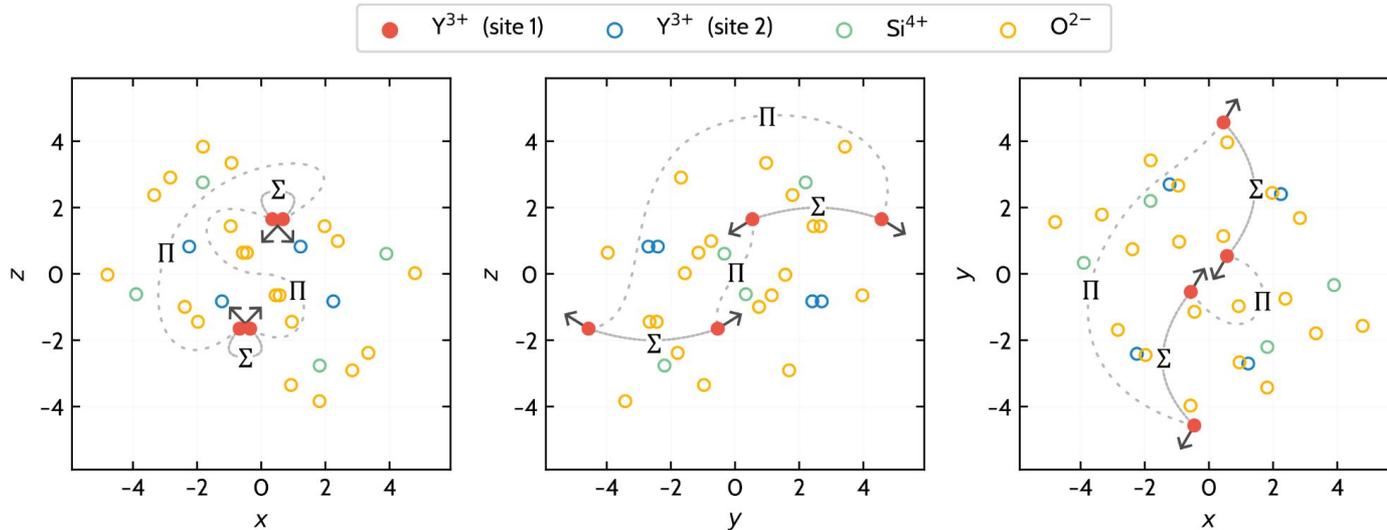
Electric
quadrupole

Magnetic
moment

Ion
electric
dipole

T-odd,
P-odd
parameter

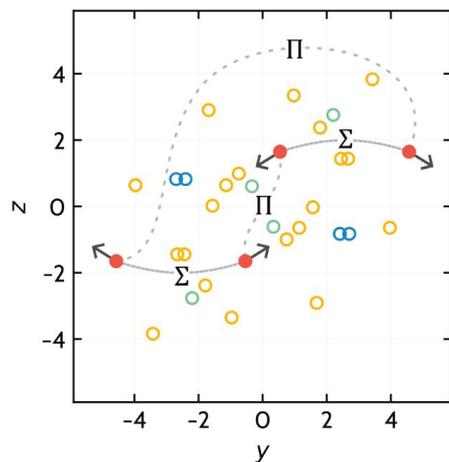
Four distinct sites in YSO



Four sites within the primitive cell of the lattice that are related by

- inversion $\hat{\Pi} : (x, y, z) \rightarrow (-x, -y, -z) \quad \pi = \pm 1$
- xy reflection $\hat{\Sigma} : (x, y, z) \rightarrow (-x, -y, z) \quad \sigma = \pm 1$

Site dependent Hamiltonian

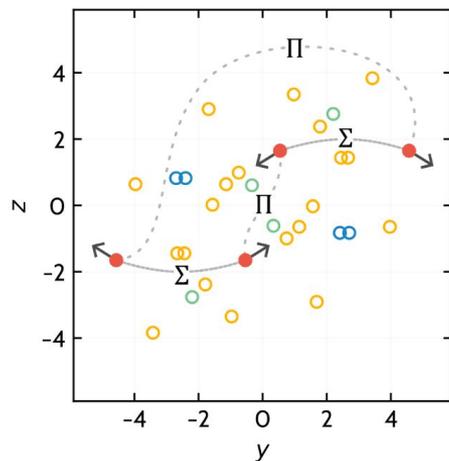


$$\hat{\Pi} : (x, y, z) \rightarrow (-x, -y, -z) \quad \pi = \pm 1$$

$$\hat{\Sigma} : (x, y, z) \rightarrow (-x, -y, z) \quad \sigma = \pm 1$$

$$H(\sigma, \pi) =$$

Site dependent Hamiltonian

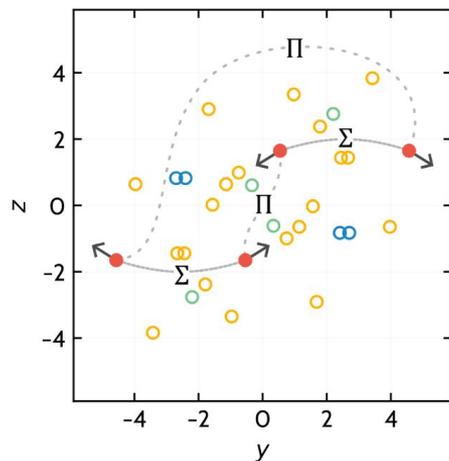


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$$\hat{\Sigma} : (x, y, z) \rightarrow (-x, -y, z) \quad \sigma = \pm 1$$

$$H(\sigma, \pi) = \sum_{i,j} Q_{ij} I_i I_j$$

Site dependent Hamiltonian

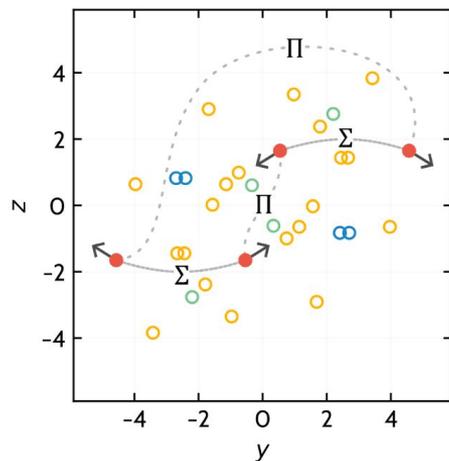


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$$H(\sigma, \pi) = \sum_{i,j} Q_{ij} I_i I_j - \sigma (\mu_x \mathcal{B}_x + \mu_y \mathcal{B}_y) - \mu_z \mathcal{B}_z$$

Site dependent Hamiltonian

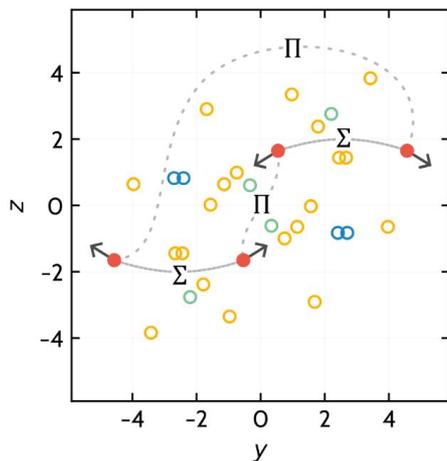


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Site dependent Hamiltonian

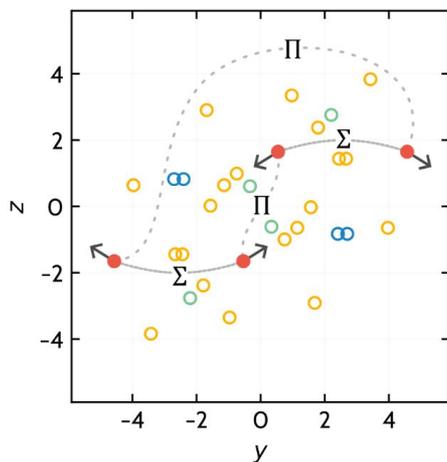


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Site dependent Hamiltonian



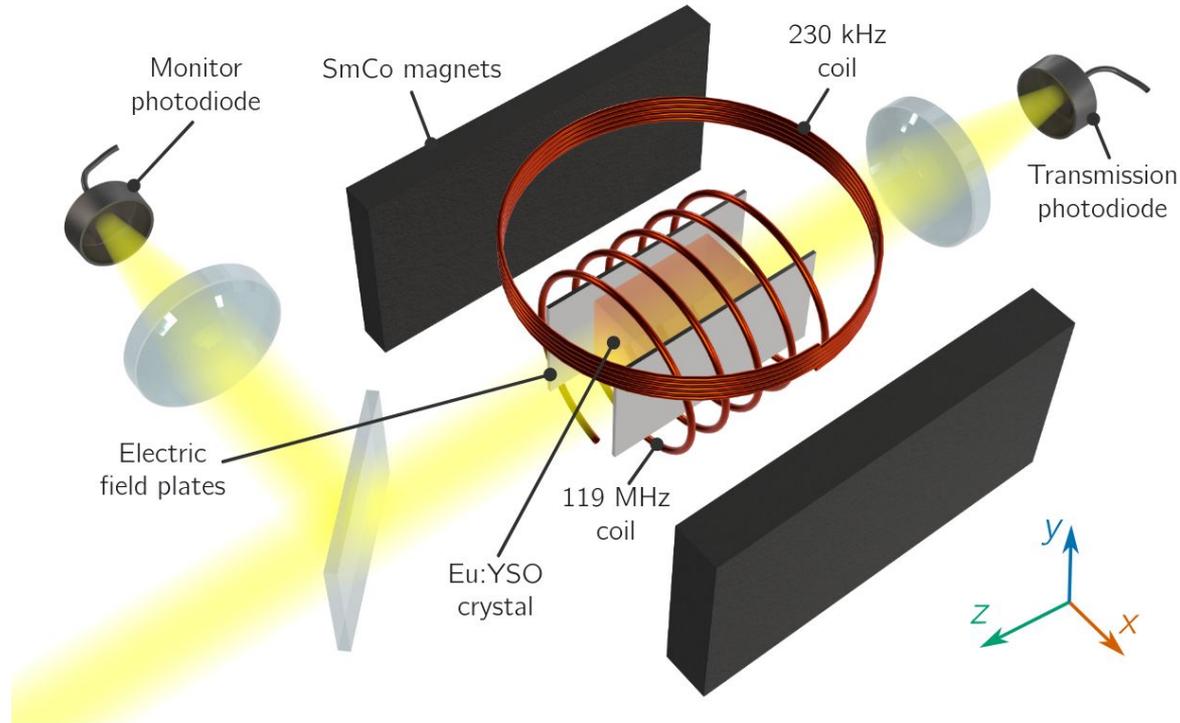
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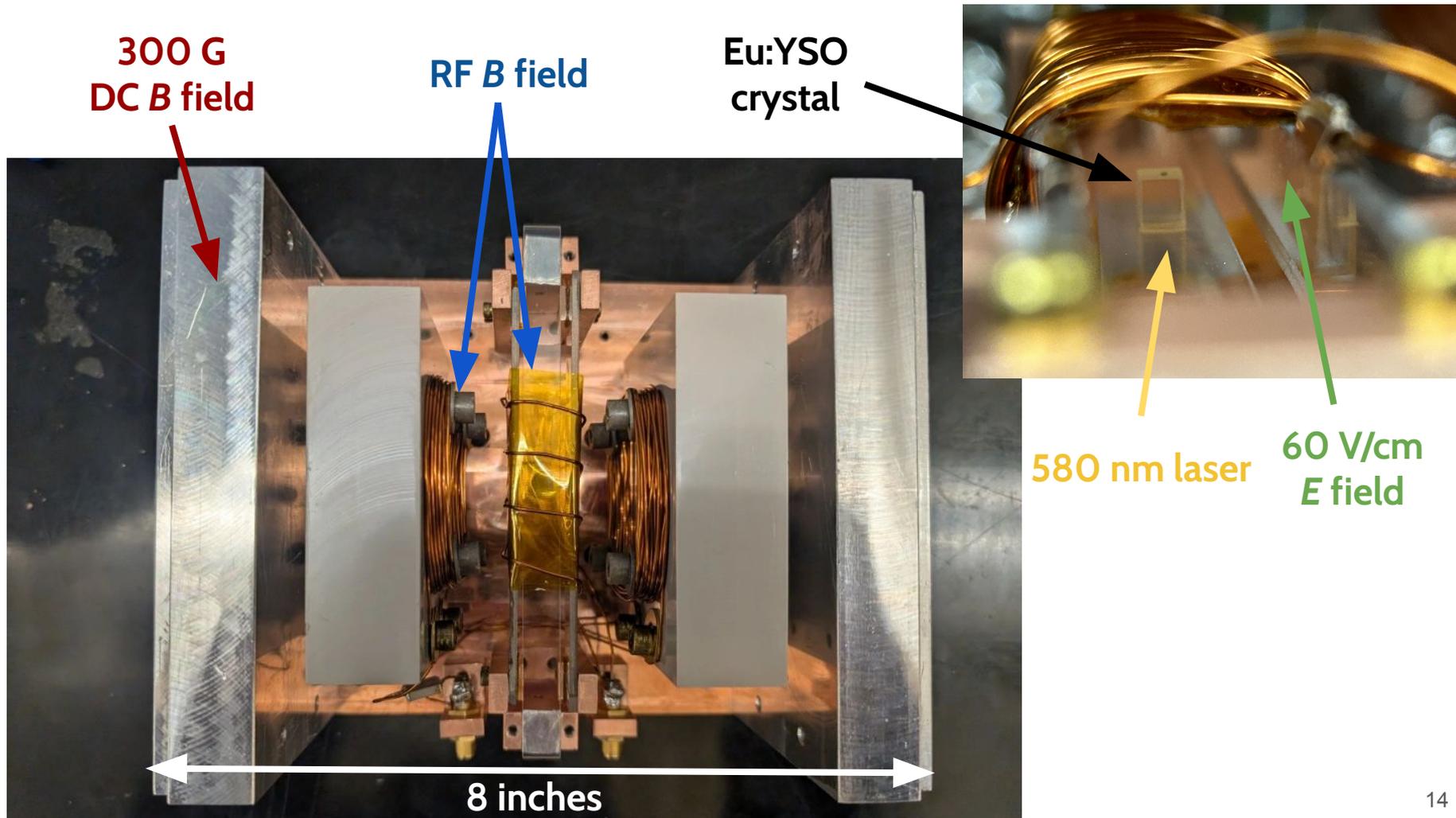
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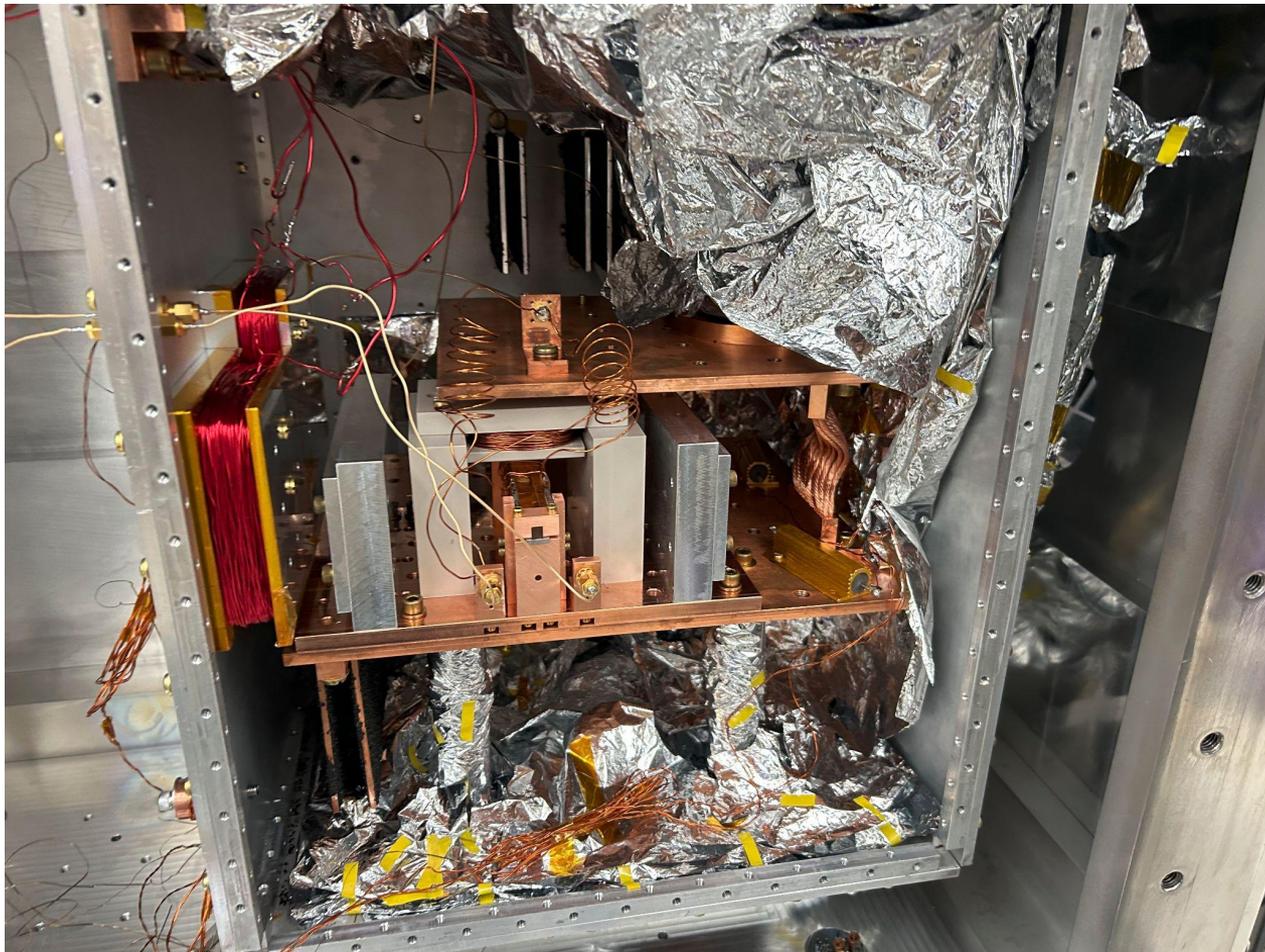
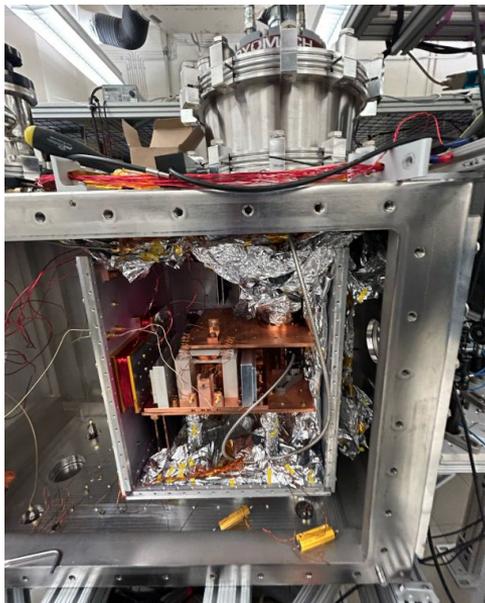
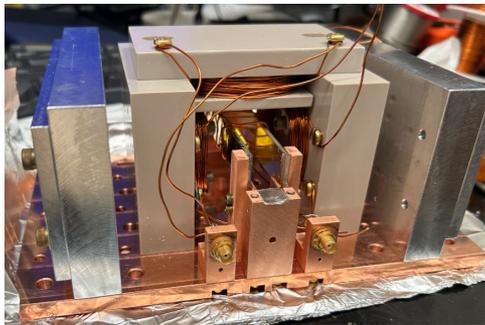
$$H(\sigma, \pi) = \sum_{i,j} Q_{ij} I_i I_j - \sigma (\mu_x \mathcal{B}_x + \mu_y \mathcal{B}_y) - \mu_z \mathcal{B}_z - \sigma \pi D \hat{n} \cdot \vec{\mathcal{E}} + \pi \Omega \vec{I} \cdot \hat{n}$$

π ensembles are identically shifted by the magnetic field and oppositely shifted by P-odd T-odd moments

Crystal mount apparatus

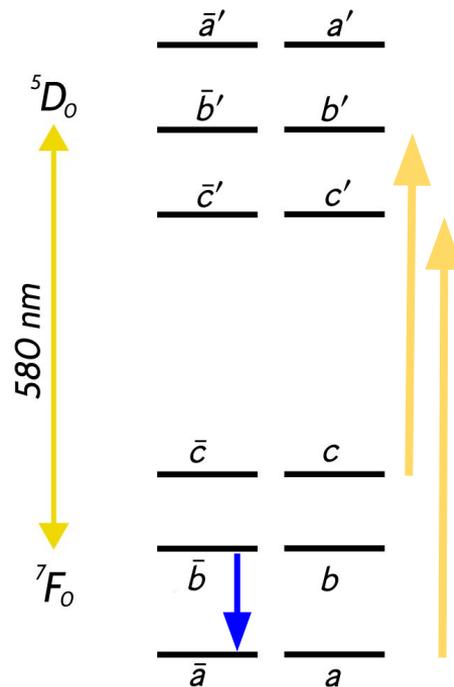






State preparation

- Excited electronic state has a 1.9 ms lifetime
- Optical and rf state preparation
 - Empty out ground state a , \bar{a} and c optically
 - Adiabatic RF sweep between \bar{b} and \bar{a}
 - Repeat
- Prepared in b and ready to do spectroscopy

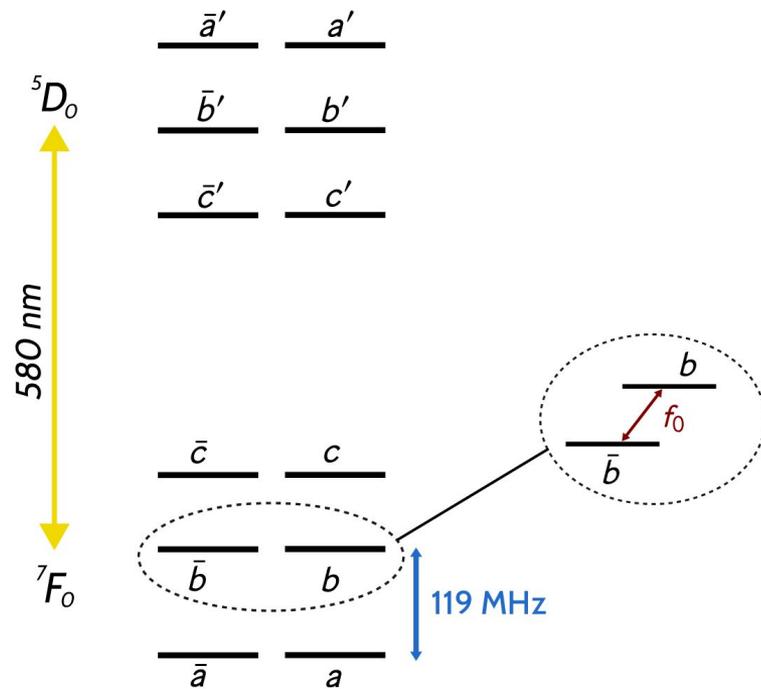


Ramsey spectroscopy

- Ramsey spectroscopy on $\bar{b} - b$ transition in a 300 G magnetic field with a 230 kHz coil

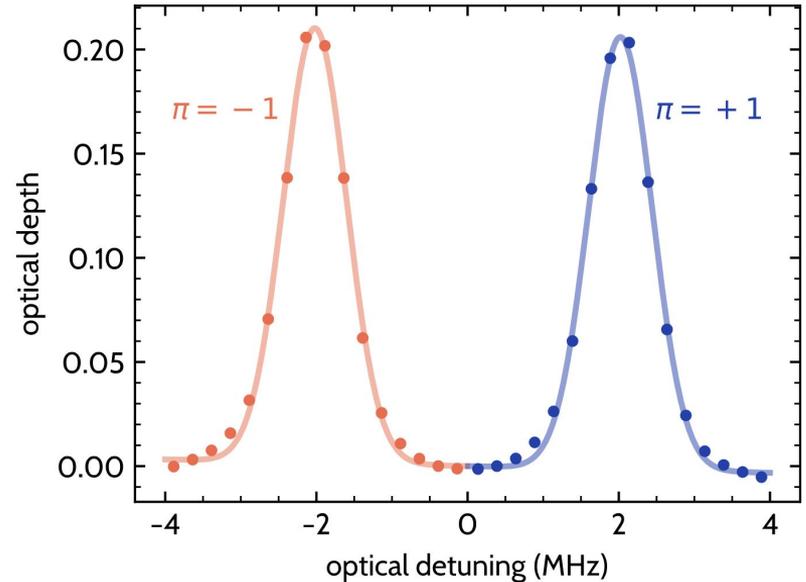
$$T_2 \sim 30 \text{ ms}$$

$$T_2^* \sim 2 \text{ ms}$$



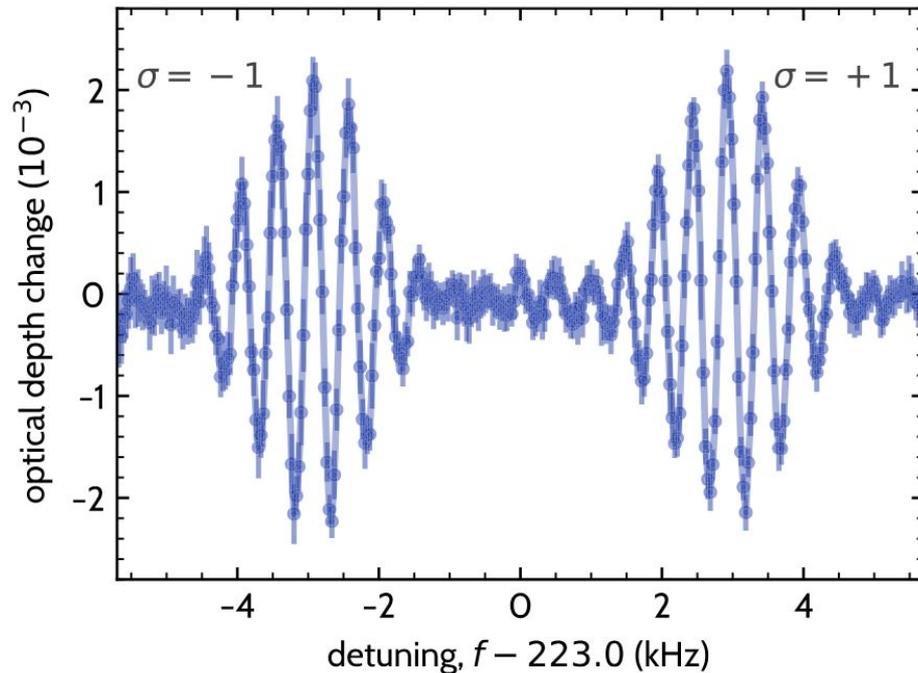
Optical detection

- Optically detect change in b
- During detection turn on the 65 V/cm lab electric field to distinguish oppositely-polarized ions



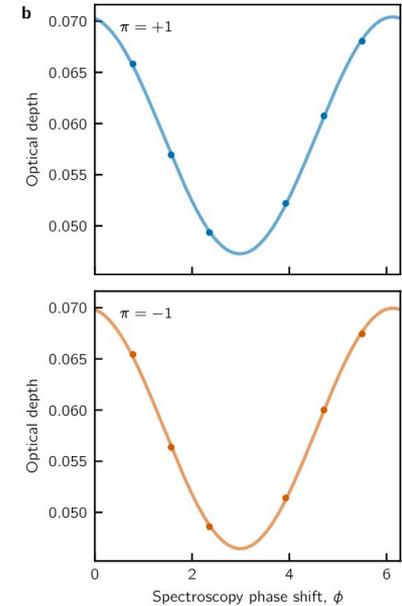
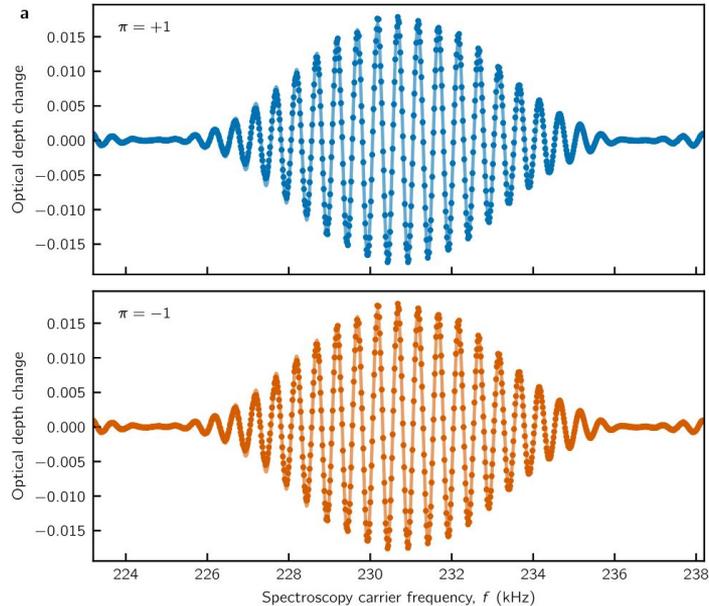
Ramsey spectrum

- We can also distinguish the σ sub-ensembles during RF spectroscopy
- Using a lab magnetic field along the laser axis
- Useful systematic test



Phasor Ramsey technique

- A modified version of Ramsey's method is used
- The carrier frequency is fixed and the second Ramsey pulse's phase is swept

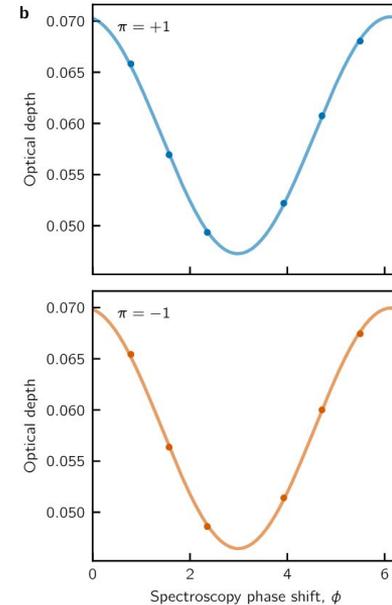


Phasor Ramsey technique

- The phase sweep is fitted to a cosine to measure the $b - \bar{b}$ line center frequency

$$A(f, \phi) = A_0 \cos \{ \phi + 2\pi [f - f_0(b\bar{b})] T \}$$

- Six phases measured for a simultaneous frequency measurement of the two oppositely-polarized sub-ensembles



Common mode and differential mode

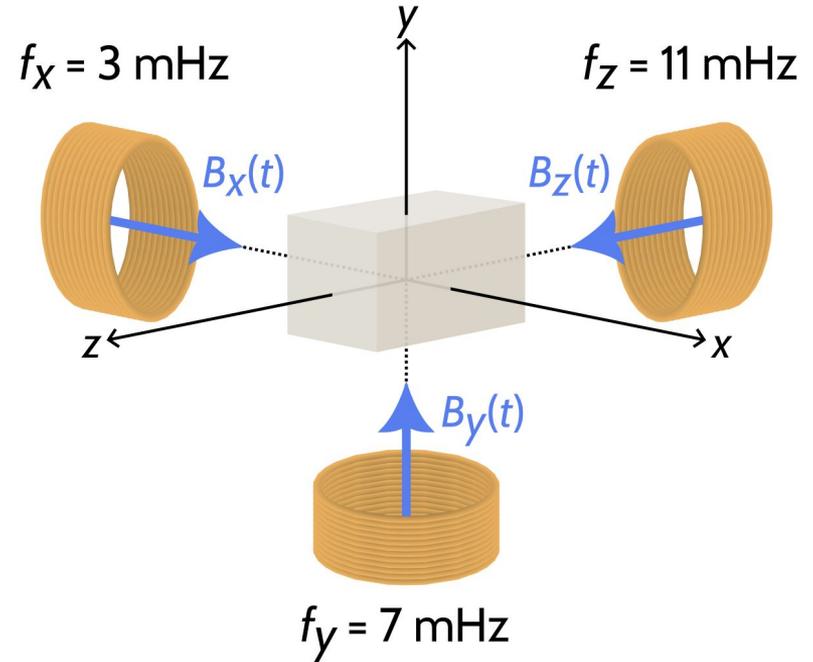
- The common mode measures magnetic field drifts
- The differential mode measures new physics, insensitive to magnetic fields

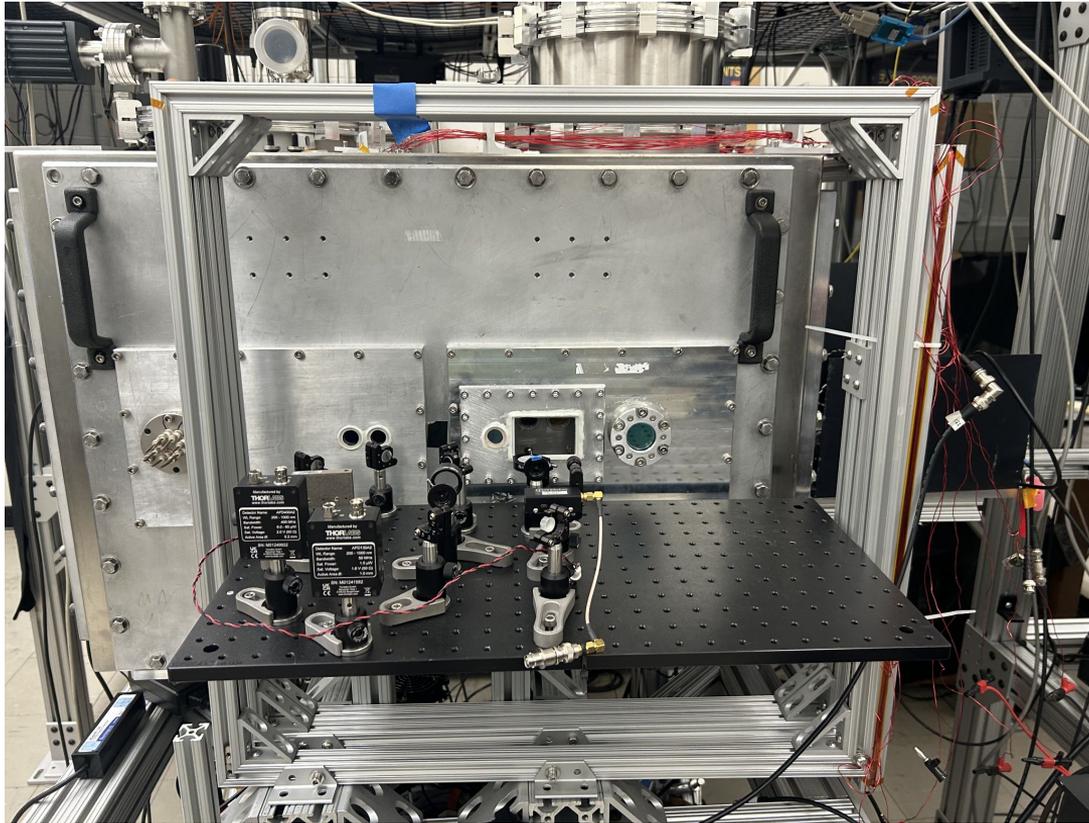
$$f_c = f_0(b\bar{b}, \pi = +1) + f_0(b\bar{b}, \pi = -1)$$

$$f_d = f_0(b\bar{b}, \pi = +1) - f_0(b\bar{b}, \pi = -1)$$

Comagnetometry test

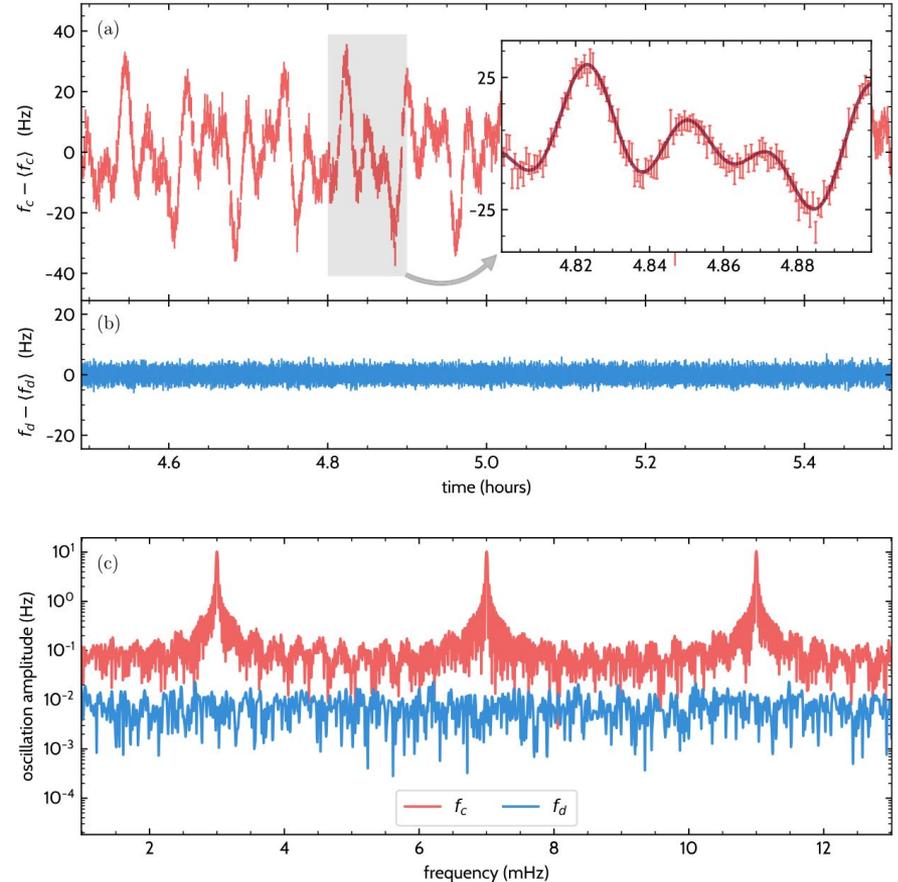
- Demonstration of how well our comagnetometer platform rejects magnetic field fluctuations
- Purposefully apply low frequency magnetic fields along each axis simultaneously
- Test *without* magnetic shielding





Comagnetometry results

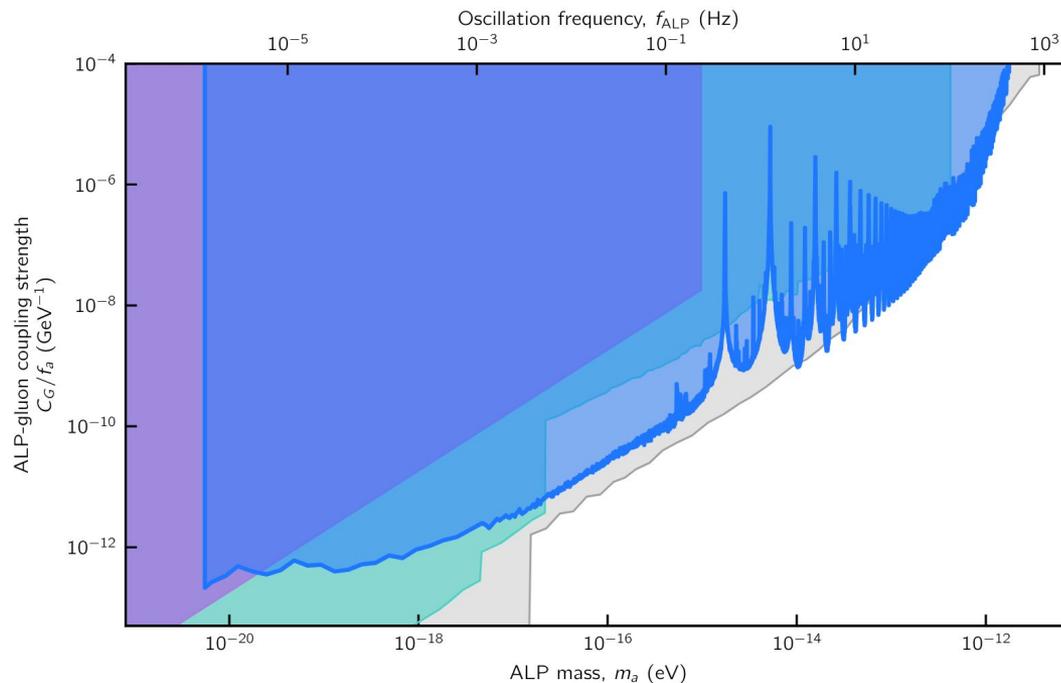
- Oscillations show up in the common mode, but not in the differential mode
- Differential mode effectively shielded to better than 10 μG drifts without magnetic shielding



Axion-like particle (ALP) search

M Fan, B Nima, A Radak, G Alonso-Álvarez, A Vutha,
arXiv:2410.02218

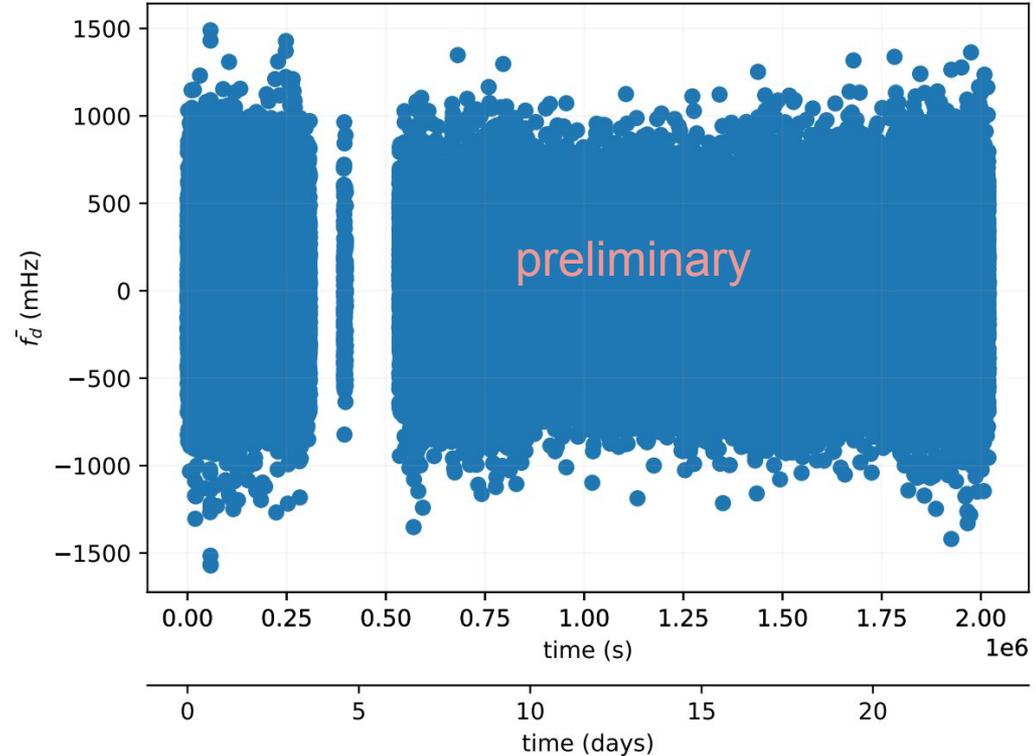
- 95% confidence exclusion region for Eu:YSO (blue)
- Comparison with
 - Trapped neutron and neutron beam (gray)
 - Clock comparisons (teal)
 - HfF⁺ eEDM (purple)



Current static T-violation measurement

- Approx. 20 mHz rt-hr
- Integrating over 3 weeks:

$$\delta f_d \cong 1 \text{ mHz}$$



Averaging down

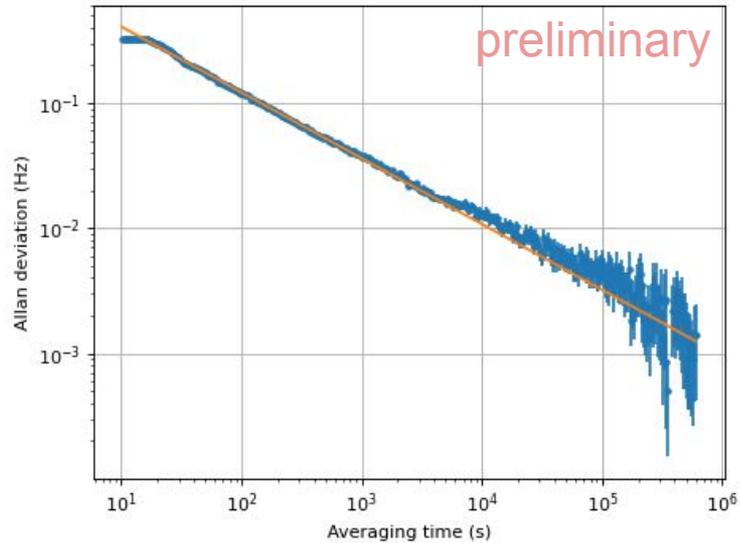


Fig: Allan deviation

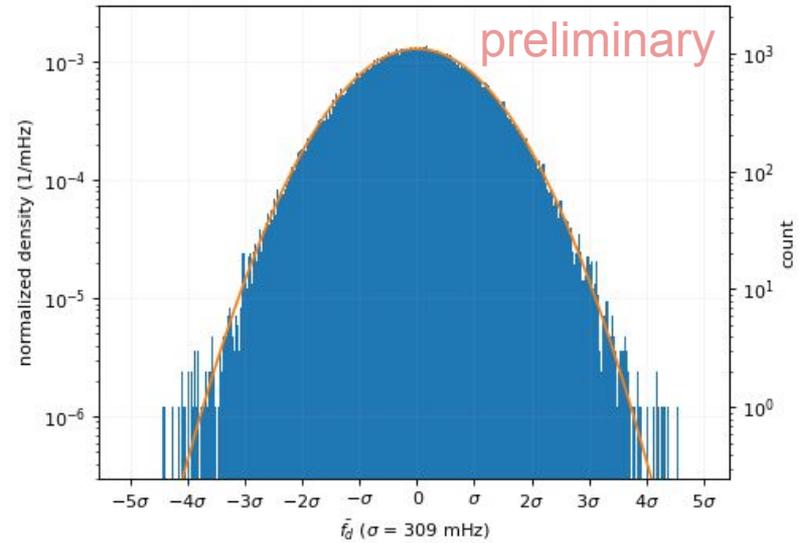
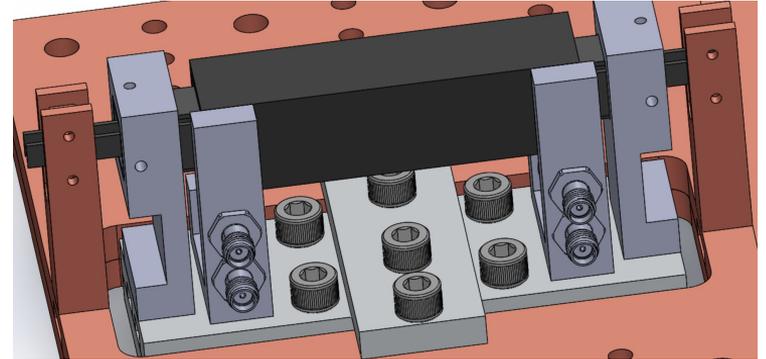


Fig: Histogram (log scale)

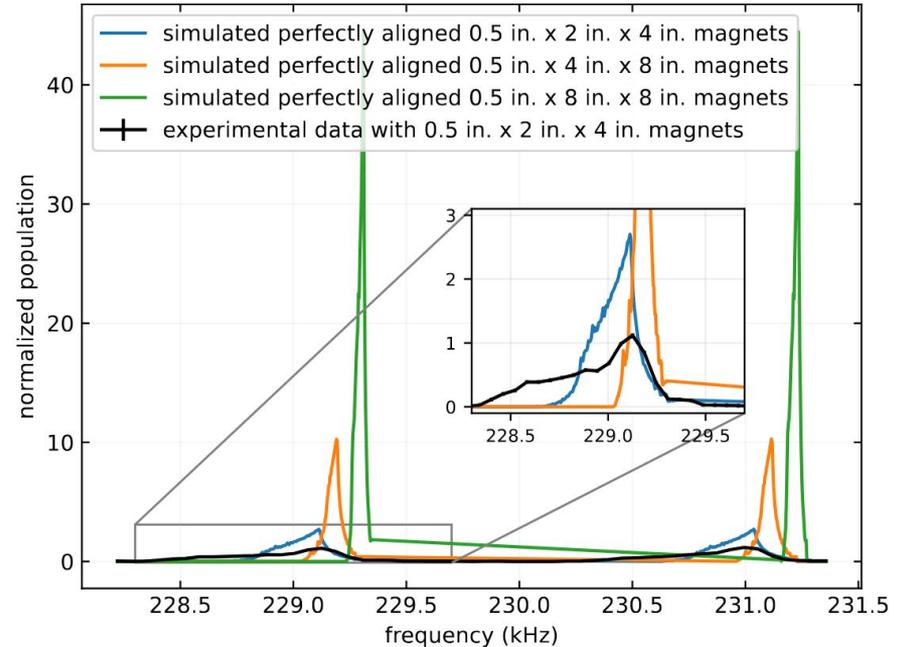
Improvement #1: Next generation crystal mount

- The Eu:YSO crystal is decoupled from all rf sources to reduce heating the crystal
- The electric field homogeneity is improved by a factor of 30
- The rf magnetic field strength and homogeneity is improved
- Ability to probe $a - \bar{a}$, $b - \bar{b}$, $c - \bar{c}$ in consecutive cycles



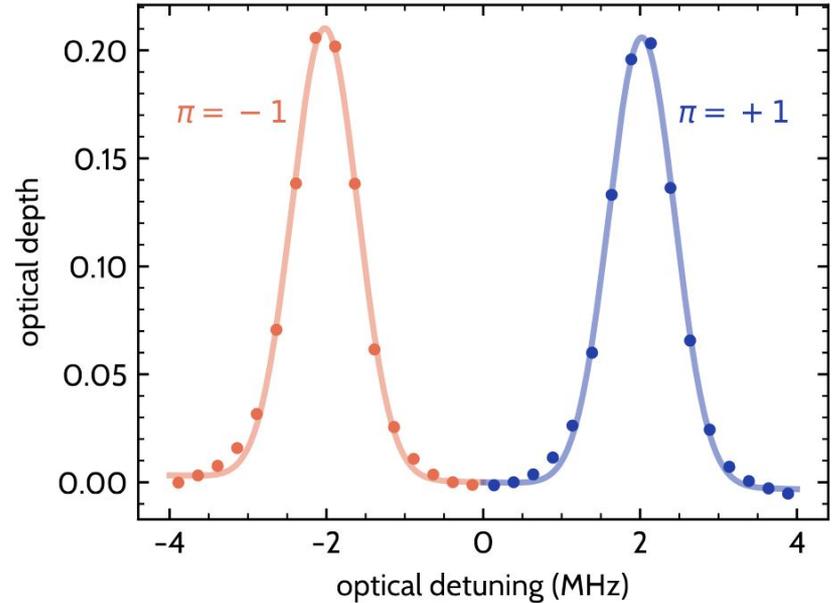
Improvement #2: Bar magnet alignment

- In the current apparatus, magnetic field gradients result in 500 Hz line broadening
- This inhomogeneity can be improved by at least a factor of 10



Improvement #3: Comb spectroscopy

- We probe about 1 in 1000 ions in the crystal
- Optical transition is broadened to ~700 MHz
- Comb spectroscopy would allow us to simultaneously probe more ions in the crystal, increasing sensitivity by orders of magnitude



Thank you

Team

Mingyu Fan
Alek Radak
Amar Vutha

Collaborators

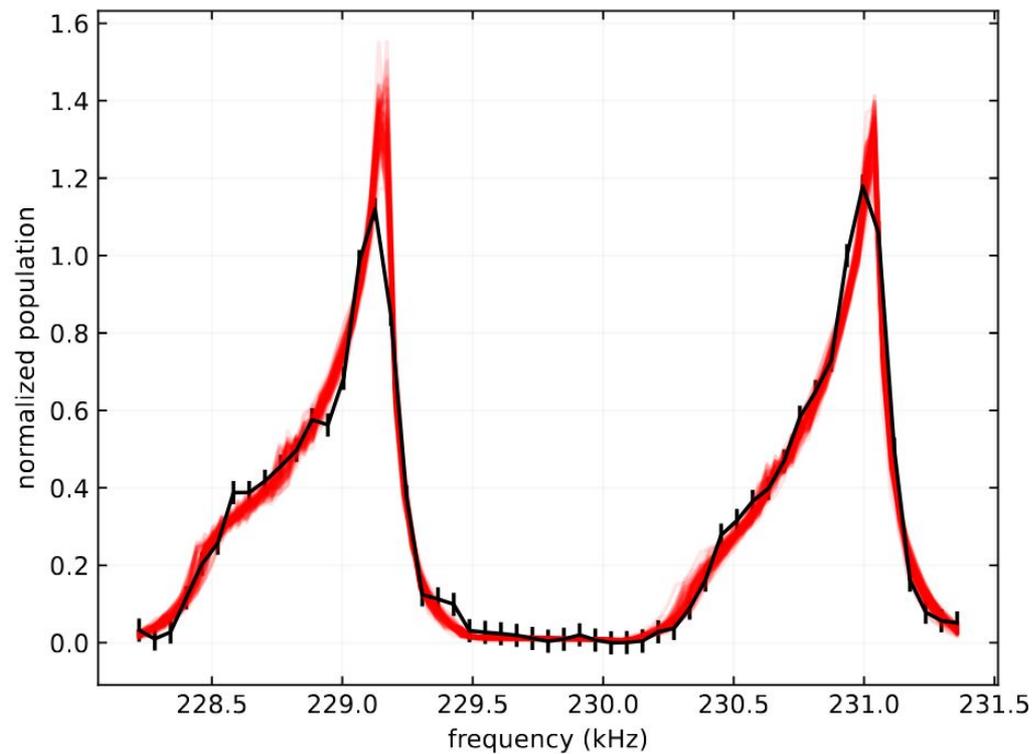
Gonzalo Alonso-Álvarez, UofT

Simon Poon, UCSB
Fletcher Hoppe, UCSB
Andrew Jayich, UCSB

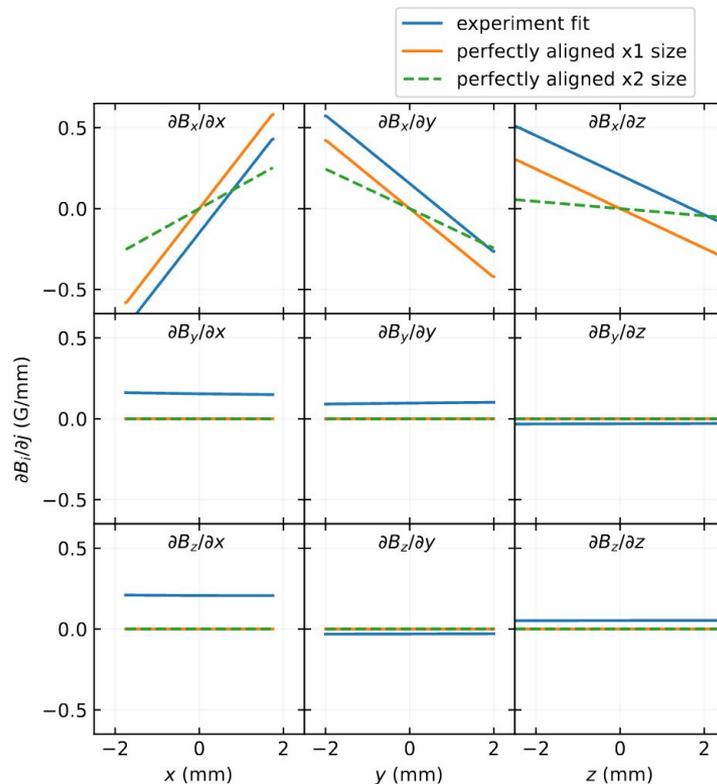
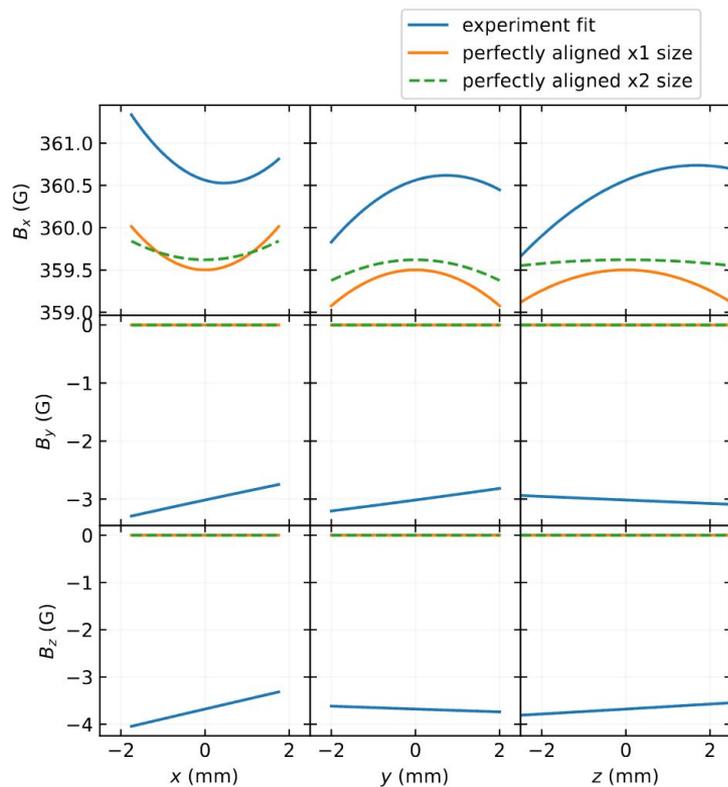


Thank you

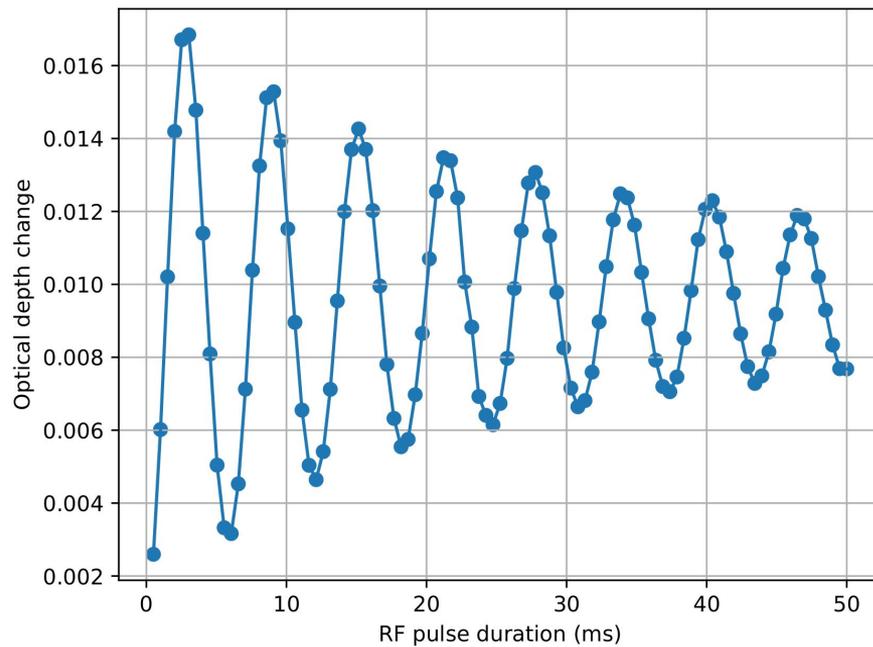
Inhomogeneous broadening & fitting



Inhomogeneous broadening & fitting



Rabi flopping



Spin echo

